9th International Conference on Hot Sheet Metal Forming of High-Performance Steel — CHS² 2024
27–29 May 2024, Nashville, Tenn., USA
10.33313/512/A0901

Press Hardening as a Sustainable Solution for Lightweight Chassis Construction in Heavy-Duty Vehicles From a LCA Perspective

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Abstract

Currently, weight reduction in vehicles is a crucial concern for mitigating air pollution and also to achieve net zero emissions vehicles by 2035. Press hardening offers a huge lightweight potential, for thick sheet applications, as those used to construct heavy-duty vehicles. The use of press hardened steels can give up to 40% weight reduction in chassis components, in comparison with current solutions. Aimed to boost the application of such solution in heavy-duty vehicles, the present work addresses the environmental benefits of using press hardening from an environmental perspective. Two cases were compared, the current solution, based on cold forming, and the proposed press hardening approach. In both cases, the study follows a cradle-to-grave life cycle assessment approach, including raw material extraction, component manufacturing, vehicle use, and end-of-life. To ensure a high level of precision in the analysis, extensive primary data from the manufacturing stage and a comprehensive use of the vehicle were utilized, encompassing three different powertrain options for HDV of vehicles in a European context: Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV) and Plug-in Hybrid Electric Vehicle (PHEV). In terms of the manufacturing stage, the production of the press hardened component had the most significant impact due to the substantial energy needed during its processing (furnace). Nevertheless, this stage's overall effect on the entire Life Cycle Assessment (LCA) was relatively minor because the advantages of weight reduction during the vehicle use stage made a substantially larger contribution. Significantly, HEV had the most pronounced impact, largely due to their consumption of fossil fuels. Conversely, BEV, when considering an average European electric mix, exhibited a more favorable environmental profile. This work showcases the environmental significance of lightweighting through press hardening in chassis part of heavy-duty electric vehicles.

1 Introduction

The transport sector, a significant contributor to adverse environmental impacts [1], is key to EU's ambitious climate goals outlined in directives like the Green Deal. In the EU, transportation currently constitutes a substantial portion of greenhouse gas (GHG) emissions, necessitating urgent action [1]. The Green Deal outlines a roadmap for making a sustainable EU economy aiming for net zero emissions by 2035 and carbon neutrality by 2050[2], requiring emissions reductions across sectors, including road transport. Among the key strategies within the EU's framework is vehicles weight reduction to enhance fuel efficiency and cut emissions, aligning with the EU principles of circular economy and sustainable resource management[3]. Efforts, mainly through advanced high strength steels (AHSS), and press hardened steels have cut passenger's cars weight by up to 30%. However, heavy-duty vehicles (HDV), which currently account for about 25% of GHG emissions from road transport[4] have received less attention in lightweighting. As passenger car travel decreases, HDV emissions are projected to exceed those from cars and motorcycles.

Recent truck developments include AHSS and press hardening steels, but still most of the chassis' components are manufactured by microalloyed high strength steels. Steels are the perfect material family candidate to achieve high weight reduction in HDV while improving part durability at affordable cost and environmental impact in a short time frame. Press hardening of Boron steels is widely used in the automotive industry to obtain very high strength components with complex shapes. The technology is mature in Europe so the well-established innovations in the automotive industry can be transferred to HDV components to attain relevant weight reductions and directly contribute to the EU's commitment to reducing the carbon footprint of the transport sector. As the EU pushes for the adoption of alternative materials and innovative manufacturing processes, the exploration of new solutions becomes imperative to meet regulatory requirements and environmental targets. In this sense, press hardening, emerges as an interesting technology to effectively address lightweighting of HDV's chassis and meet the EU's objectives of promoting energy-efficient and environmentally friendly transportation.

Accordingly, the aim of this work is to conduct a comprehensive assessment of the life cycle impacts associated with the utilization of press hardening steels for lightweight chassis construction in HDV. The work endeavors to provide actionable insights that align with the principles of the European Green Deal and contribute to the transition towards a more sustainable transport ecosystem within the European Union.

2 Case Study and Materials

In this work a cross member beam for HDV has been used as a case study. Cross member beams are positioned between the two long frame members in trucks, see **Figure 1**. There are usually different designs of the cross members, depending on how much space is available due to parts like drive shaft, gear box and exhaust system. If no parts interfere with the design of the cross member, then the design can be quite simple (green part). The red part shows an example of max interference, where the design needs to be much more complicated to be able to transfer the same forces and torque. The forces the cross member need to transfer come from when the two frame members move independently of each other. Parts mounted on the outside of the frame members, for example fuel tank and battery, are exposed to accelerations during normal use of the truck and will expose the cross member to torque. The stress levels the cross member are exposed to during normal use of the truck are below the yield strength of the material, but since the stress will oscillate there is a risk for fatigue.

Current state of the art solutions for cross member beams are typically produced by cold forming in hot rolled steels up to 9 mm sheet thickness. In this case study, a cross member beam with double symmetric cross sections was produced and analyzed, see **Figure 1**. The cross-member beam was produced by press hardening of 22MnB5 steel of 6 mm sheet thickness. **Table 1** summarizes the main mechanical properties of the current solution made of a microalloyed steel with an ultimate strength of about 350 MPa (named as 355MC) and manufactured by cold forming. The proposed solution in press hardened 22MnB5 steel (**Table 1**) is dimensioned to achieve at least the same fatigue performance as the reference part manufactured by cold forming.

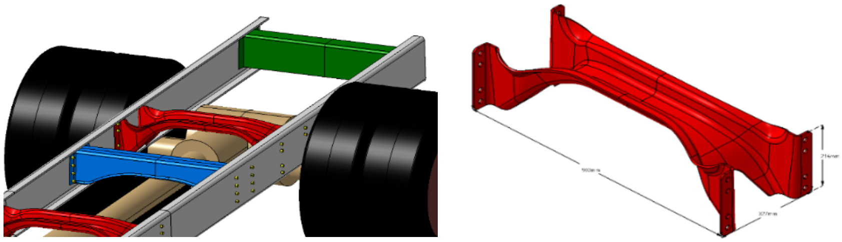

Figure 1. *Cross member beam used in case study and its location in a truck.*

Table 1: *Tensile properties for cold forming steel (355MC) and press hardening steel (22MnB5) used in case study.*

Material	Yield Strength [MPa]	Tensile Strength [MPa]	Elongation [A50 %]
355MC	>355	430-550	23
22MnB5	1028	1561	10

3 LCA Methodology

Life Cycle Assessment (LCA) stands as a well-established methodology to identify, describe, and evaluate the environmental aspects and possible effects of a product, process, or service throughout its entire life cycle. This involves creating a list of relevant inputs and outputs of a product system to assess its potential environmental impacts. It provides a comprehensive quantification of relevant emissions, resource consumption, associated environmental and health impacts, as well as resource depletion issues attributed to goods or services. The international standards ISO 14040[5] and ISO 14044[6] delineate the core framework and principles of LCA methodology, encompassing four interrelated phases: defining goal and scope, conducting inventory analysis, assessing impacts, and interpreting results. Additionally, the SPE-14040-1475 standard [7], developed by the CSA group, sets forth guidelines for performing comparative LCAs of automotive parts, which consider alterations in weight resulting from shifts in materials, manufacturing methods, or part geometry.

This study's original contribution to LCA lies in its application to the environmental analysis of cross member beams made with Hot forming high-strength steel for electric vehicles within the European Union context. The LCA process is structured into four phases, which will be detailed in subsequent sections: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation.

3.1 Goal and Scope Definition

A cradle-to-grave approach has been adopted to study the environmental performance. This study identifies three primary life cycle stages: The initial stage encompasses raw material extraction, manufacturing, and assembly; the second stage involves the operational phase of an electric vehicle (EV); and the final stage consists of end-of-life considerations.

System boundaries encompass the production of the demonstrator, its operational phase, and end-of-life management. Accordingly, the primary inputs considered include energy and materials. This approach ensures a comprehensive assessment of the environmental and cost implications throughout the entire life cycle of the cross-member beam under study.

Within the raw material extraction, manufacturing and assembly stage, the specific steps to produce a Cross member beam are depicted in **Figure 2** for cold stamping and press hardening processes.

Functional unit is determined as the driving distance of 1 km. Considering a lifetime driving distance of 180.000km according to the EEA Report[8]. Calculations were carried out using Simapro v9.5 software and the ecoinvent database v3.9 and the CML Method.

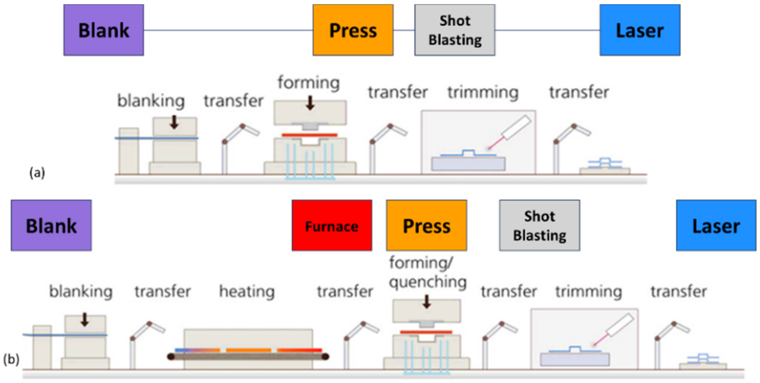

Figure 2 *(a) Cold stamping production steps. (b) Press hardening production steps.*

3.2 Life Cycle Inventory

The life cycle inventory is a composition of experimental data, suppliers' information, and literature data. The inventory for all materials and energy consumed during the raw material extraction and manufacturing stage is provided in ***Table 2*** for the cold stamping process and in for the press hardening process.

Table 2 Life Cycle inventory.

Process Step	Inputs	Cold stamping	Press Hardening	Unit
Blanking	22MnB5 steel		14,000	kg
	S355MC steel	21,000		kg
	Electricity TruLaser	0,022	0,747	kWh
	Electricity for transfer	1,120	0,060	kWh
	Cutting gas Oxygen	0,007	0,005	m3
	Transport Rail	54,600	36,400	tkm
Furnace	Roller Furnace		1,330	kWh

	Electricity for transfer		0,060	kWh
Stamping	Stamping press	0,650	0,660	kWh
	Electricity for transfer	0,060	0,060	kWh
Shot blasting	Shot blasting equipment	0,849	0,567	kWh
	Electricity for transfer	0,060	0,060	kWh
	Shot blasting abrasive	0,065	0,044	kg
Laser	Cutting gas Oxygen	0,007	0,005	m3
	Electricity TruLaser	1,120	0,747	kWh
	Electricity for transfer	0,060	0,060	tkm
	Steel scrap	2,100	1,400	kg

During the use stage, average fuel and energy consumption for different types of vehicles powertrain are depicted on **Table 3** for internal combustion engine vehicle (ICEV) battery electrical vehicle (BEV), hybrid electric vehicle (HEV) and plug-in electric vehicle (pHEV). Energy consumption has been calculated based on the EEA Report[8] and considering electric powertrains as 100% for BEV, 30% for HEV and 50% for pHEV according to Tagliaferri et al. [9] and fuel consumption for HEV and PHEV as 50.04 mL/km, based on Ecoinvent 2.2 Report [10]. End-of-life has been considered based on Europe statistics published by Eurostat[11] as 44% collected and treated for recycling.

***Table 3** Energy and fuel consumption during Use stage for different vehicles powertrain technology. In parenthesis the % of electric powertrain*

BEV	ICEV	HEV (30%)		PHEV (50%)	
Energy consumed during lifetime per kg of vehicle	Fuel consumed during lifetime per kg of vehicle	Energy consumed during lifetime per kg of vehicle	Fuel consumed during lifetime per kg of vehicle	Energy consumed during lifetime per kg of vehicle	Fuel consumed during lifetime per kg of vehicle
20,09 kWh/kg	5585,86 mL/kg	6,03 kWh/kg	3910,10 mL/kg	10,05 kWh/kg	2792,93 mL/kg

4 Life Cycle Impact Assessment Results

In accordance with the mandatory elements stated in the ISO 14044:2006 standard[6], the selection of impact categories, category indicators and characterization models is mandatory for each and all LCA. For this study, selected impact assessment method is CML-IA (baseline, version 3.08).

Findings are organized based on the predefined life cycle stages outlined in the goals and scope, offering a summary of the environmental performance from a broad perspective across each life cycle stage. Results are presented for the three options of vehicles for cold stamped cross member beam in ***Table 4*** and for press hardened cross member beam in **Table 5**.

***Table 4** Cold stamping manufacturing LCA Results.*

Impact category	Raw material extraction, manufacturing and assembly	Use stage BEV	Use stage HEV	Use stage pHEV	EoL	BEV	HEV	pHEV
Abiotic depletion	5,08E-05	3,51E-04	5,95E-03	4,35E-03	2,24E-08	4,02E-04	6,00E-03	4,40E-03
Abiotic depletion (fossil fuels)	6,40E+02	1,64E+03	6,05E+03	4,79E+03	4,99E-01	2,28E+03	6,69E+03	5,43E+03

Global warming (GWP100a)	6,79E+01	1,45E+02	4,57E+02	3,68E+02	3,57E-02	2,13E+02	5,25E+02	4,36E+02
Ozone layer depletion (ODP)	1,03E-06	6,28E-06	6,54E-05	4,85E-05	5,19E-10	7,30E-06	6,64E-05	4,95E-05
Human toxicity	1,88E+01	7,53E+01	4,96E+02	3,76E+02	7,57E-02	9,41E+01	5,15E+02	3,95E+02
Fresh water aquatic ecotox.	2,24E+01	1,00E+02	3,82E+02	3,01E+02	2,19E+00	1,25E+02	4,06E+02	3,26E+02
Marine aquatic ecotoxicity	3,99E+04	2,60E+05	4,46E+05	3,93E+05	6,55E+02	3,01E+05	4,87E+05	4,33E+05
Terrestrial ecotoxicity	6,65E-02	4,41E-01	5,73E-01	5,35E-01	7,62E-05	5,07E-01	6,39E-01	6,02E-01
Photochemical oxidation	2,05E-02	2,74E-02	7,75E-02	6,32E-02	6,93E-06	4,79E-02	9,80E-02	8,37E-02
Acidification	2,03E-01	6,69E-01	1,81E+00	1,48E+00	2,21E-04	8,72E-01	2,01E+00	1,69E+00
Eutrophication	7,57E-02	4,99E-01	5,87E-01	5,62E-01	5,76E-05	5,75E-01	6,63E-01	6,38E-01

Table 5 *Press hardening LCA Results*

Impact category	**Raw material extraction, manufacturing and assembly**	**Use stage BEV**	**Use stage HEV**	**Use stage pHEV**	**EoL**	**BEV**	**HEV**	**pHEV**
Abiotic depletion	2,18E-04	2,34E-04	3,97E-03	2,90E-03	2,02E-08	4,52E-04	4,18E-03	3,12E-03
Abiotic depletion (fossil fuels)	4,73E+02	1,09E+03	4,03E+03	3,19E+03	4,49E-01	1,56E+03	4,51E+03	3,67E+03
Global warming (GWP100a)	4,95E+01	9,68E+01	3,05E+02	2,45E+02	3,21E-02	1,46E+02	3,54E+02	2,95E+02
Ozone layer depletion (ODP)	7,26E-07	4,18E-06	4,36E-05	3,23E-05	4,67E-10	4,91E-06	4,43E-05	3,31E-05
Human toxicity	2,85E+01	5,02E+01	3,31E+02	2,51E+02	6,82E-02	7,88E+01	3,60E+02	2,79E+02
Fresh water aquatic ecotox.	1,77E+01	6,69E+01	2,54E+02	2,01E+02	1,97E+00	8,65E+01	2,74E+02	2,21E+02
Marine aquatic ecotoxicity	3,60E+04	1,73E+05	2,97E+05	2,62E+05	5,90E+02	2,10E+05	3,34E+05	2,98E+05
Terrestrial ecotoxicity	4,97E-01	2,94E-01	3,82E-01	3,57E-01	6,86E-05	7,91E-01	8,79E-01	8,54E-01
Photochemical oxidation	1,46E-02	1,83E-02	5,17E-02	4,21E-02	6,24E-06	3,29E-02	6,63E-02	5,68E-02
Acidification	1,60E-01	4,46E-01	1,21E+00	9,90E-01	1,99E-04	6,06E-01	1,37E+00	1,15E+00
Eutrophication	6,03E-02	3,33E-01	3,91E-01	3,75E-01	5,18E-05	3,93E-01	4,52E-01	4,35E-01

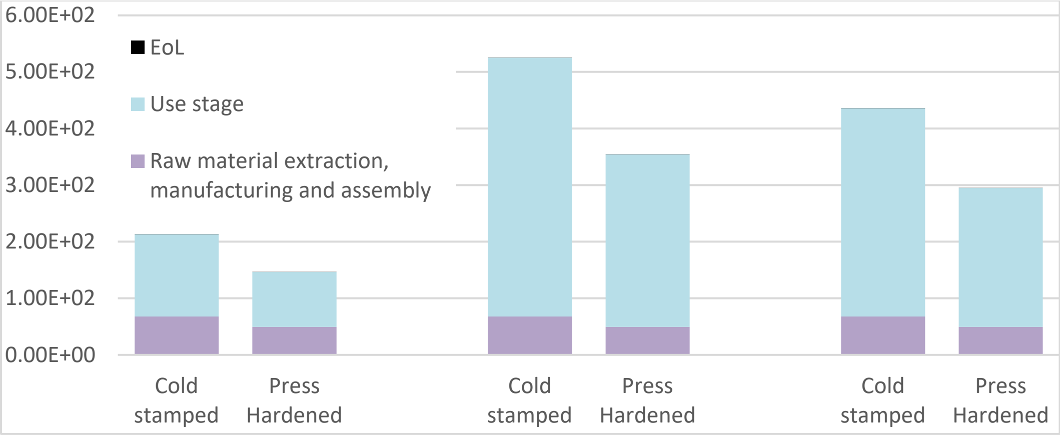

Figure 3 presents the comparison results for global warming potential of both technologies to manufacture a cross member beam, cold stamping, and press hardening. Results are in kg of CO2 equivalent for a driving distance of 1 km considering all life cycle stages of a cross member beam.

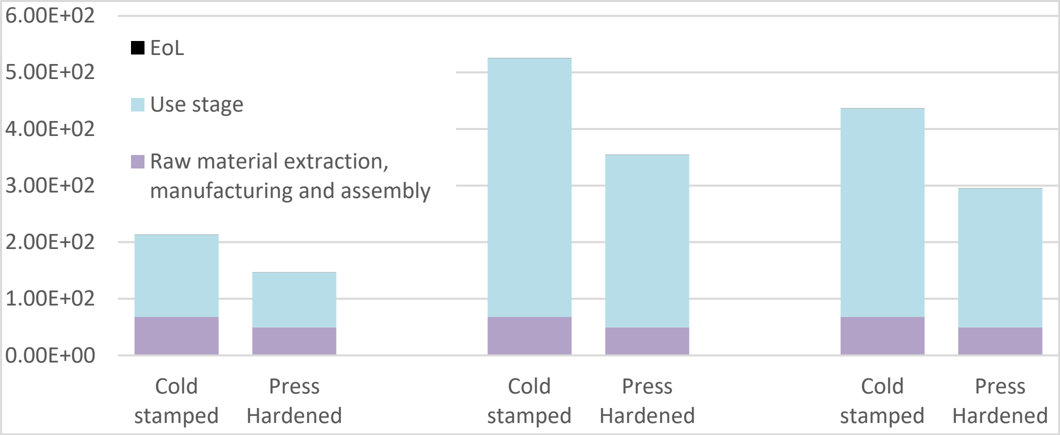

***Figure 3** Global warming comparison for different types of HDV: BEV, HEV and pHEV.*

5 Interpretation and Concluding Remarks

Results indicate that cross member beams manufactured through press hardening processing generally exhibit lower environmental impacts across most impact categories compared to those produced using cold stamping routes. Specifically, press hardened cross member beam demonstrates advantages with impact reduction in all impact categories except for two: abiotic depletion and fresh water aquatic ecotoxicity and only in the case of the BEV. For HEV and pHEV, press hardened process has the lowest environmental profile. In all cases, environmental gains range from 67% to 84%. Particularly, in terms of global warming potential, advantages are evident for press hardened processing of 69%, 67% and 68% for BEV, HEV and pHEV respectively. This translates to savings of 66 kg CO2 eq, 170 kg CO2 eq and 141 kg CO2 eq per km for BEV, HEV and pHEV respectively.

Evidently, use stage significantly influences environmental impact results, due to energy consumption and emissions during HDV operation that is directly related to the weight and payload of the vehicle.

Given the annual emissions attributed to road transport in Europe (800 tons CO2 eq in 2022) and accounting for the HDV segment’s 25% share, transitioning the entire fleet to an improved fleet version with 67% carbon footprint reduction would result in annual savings of 66 tons of CO2 eq.

In conclusion, the comparison of LCA results underscores the potential of press hardening technology to contribute significantly to the EU's objectives of reducing the carbon footprint of the transport sector. Findings highlight the importance of adopting innovative solutions like press hardening to address environmental challenges while meeting regulatory requirements and advancing the goals of the European Green Deal.

Acknowledgements

The authors would like to thank the European Union for providing funding of the Fatigue4Light project (Horizon 2020, LC-GV-06-2020 project no. 101006844) in which this study was conducted.

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